

Consortium for Electric Reliability Technology Solutions

White Paper on

Integration of Distributed Energy Resources

The MicroGrid Concept

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1. Overview and Introduction

Construction of new large power generating plants is not keeping pace with growing electricity demand in the west and northeast of the U.S. At the same time, customer demand for even more highly reliable power is growing across the nation. Even if a sufficient number of new generating plants were built, the country's aging transmission and distribution systems are unlikely to reliably deliver the increased power supply that is needed. Moreover, the cost of the upgrades required to enable today's power system to deliver the level of reliability being demanded is far in excess of what society has so far been willing to bear. In this context, distributed energy resources (DER), small power generators typically located at customers' sites where the energy they generate is used, have emerged as a promising option to meet customers' current and future demands for increasingly more reliable electric power. DER include electricity generators, energy storage, load control, and, for certain classes of systems, advanced power electronic interfaces between the generators and the distribution grid.

This white paper proposes that the significant potential of smaller DER (< 100 kW/unit) to meet customers' and utilities' needs can be best captured by organizing these resources into MicroGrids¹. MicroGrids are envisioned as clusters of generators (including heat recovery), storage, and loads that are operated as single controllable systems. MicroGrids can operate both connected to and synchronized with the utility distribution grid and in isolation from the utility distribution grid (as an "island"). System conditions, and more importantly, economic factors will dictate the prevailing mode of operation.

MicroGrids represent an entirely new approach to integrating DER, especially small generators, into utility distribution systems. Traditional approaches for integrating DER focus on the impacts on grid performance of one, two, or a relatively small number of individually interconnected microgenerators. An example of the traditional approach to DER is found in the Institute of Electrical and Electronics Engineers (IEEE) Draft Standard P1547 for Distributed Resources Interconnected with Electric Power Systems. This standard focuses on ensuring that interconnected generators will shut down automatically if problems arise on the utility grid. By contrast, MicroGrids would be designed to separate or island from the utility grid and continue to operate independently and serve their customers' power needs when grid problems occur, reconnecting to the grid once the problems are solved.

A critical feature of the MicroGrid is its presentation to the surrounding distribution grid as a single controllable system. Key to this characteristic is reliance on the flexibility of advanced power electronics that controls the interface between microsources and the surrounding AC system. In other words, the MicroGrid concept completely eliminates utilities' traditional concerns and approaches for integrating DER, which is to assess how many DER can be "tolerated" until their collective electrical impact begins to create problems (such as excessive current flows and voltage fluctuations) for distribution grid operation. The MicroGrid architecture insures that its electrical impact on the distribution grid is not only as a good citizen

¹ We do not address directly interconnection and integration for larger DER (those in excess of 500 kW/unit). However, we illustrate the role that MicroGrids can play as elements of larger power parks whose total installed capacity is measures in the 10's of MW.

that does no harm but also as a model citizen, adding benefits to the distribution system – reducing congestion, offsetting the need for new generation, and responding to rapid changes in load levels.

From the utility's perspective, the central advantage of a MicroGrid is that it can be regarded as a controlled element within the power system that can be operated as a single dispatchable load, which will respond in seconds to distribution system needs. Customers also benefit from a MicroGrid that is designed to meet their local needs, e.g., for uninterruptible power supply/enhanced local reliability, reduced feeder losses, supported local voltages/correction of voltage sag, and increased efficiency through use of waste heat.

This white paper explores key technical issues raised by the MicroGrid concept. Background and contextual information relevant to MicroGrids is presented in Section 2.0, which briefly describes generation technologies involved in MicroGrids and the particular role that combined heat and power generation could play in MicroGrids. Section 3.0 describes MicroGrid design and operation in detail. The following three sections delineate the key technical challenges associated with MicroGrids: their presentation to the utility grid (Section 4.0), the controls required for them to function effectively both in connection to the utility grid and in isolation (or islanded) from the grid (Section 5.0), and the protection and safety issues that must be addressed (Section 6.0). Section 7.0 discusses MicroGrid economics in detail because the business case that must be established will dictate the configuration and operation of the MicroGrid. Section 8.0 summarizes the issues presented in the paper and highlights areas of needed research. Appendices A-D examine in detail the following background and contextual issues related to MicroGrids: generation technologies, electrical issues, and environmental, and regulatory constraints.

2. Background

2.1 Technologies

Current trends in DER are toward small technologies. One important DER technology is small **gas-fired microturbines** in the 25-100 kW range, which many expect can be mass produced at low cost. These devices – which are high-speed (50,000-100,000 rpm) turbines with air foil bearings – are designed to combine the reliability of on-board commercial aircraft generators with the low cost of automotive turbochargers. Microturbines rely on power electronics to interface with loads. Example products include: Allison Engine Company's 50-kW generator, Capstone's 30-kW and 60-kW systems, and (formerly) Honeywell's 75-kW Turbogenerator.

Fuel cells are also well suited for distributed generation applications. They offer high efficiency and low emissions but are currently expensive. Phosphoric acid cells are commercially available in the 200-kW range, and solid-oxide and molten-carbonate cells have been demonstrated. A major development effort by automotive companies has focused on the possibility of using gasoline as a fuel for polymer electrolyte membrane (PEM) fuel cells. In 1997, Ballard Generation Systems formed a strategic alliance with Daimler-Benz and Ford to develop new vehicle engines using Ballard's PEM fuel cell. Fuel cell costs for these engines are expected to be \$200 per kW. Fuel cell engine designs are attractive because they promise high efficiency

without the significant polluting emissions associated with internal combustion engines. Many other major international companies are investing in fuel cells, including General Motors, Chrysler, Honda, Nissan, Volkswagen, Volvo, and Matsushita Electric.

Microturbines and fuel cells are a major improvement over conventional combustion engines in their emissions of ozone, particulate matter less 10 μm in diameter (PM-10), nitrogen oxide (NO_x), and carbon monoxide (CO). The primary fuel for microsources is natural gas, which has fewer particulates and less carbon than most traditional fuels for combustion engines. Microsources that effectively use waste heat can have CO emissions as low as those of combined-cycle generators. NO_x emissions are mainly a consequence of combustion; some traditional combustion fuels, notably coal, contain nitrogen that is oxidized during the combustion process. However, even fuels that contain no nitrogen emit NO_x, which forms at high combustion temperatures from the nitrogen and oxygen in the air. Gas turbines, reciprocating engines, and reformers all involve high temperatures that result in NO_x production. Microturbines and fuel cells have much lower NO_x emissions because of their lower combustion temperatures.

Distributed resources include more than microturbines and fuel cells. Storage technologies such as batteries, ultracapacitors, and flywheels are important. Combining storage with microsources provides peak power and ride-through capabilities during system disturbances. Storage systems have become far more efficient than they were five years ago. Flywheel systems can deliver 700 kW for five seconds, and 28-cell ultracapacitors can provide up to 12.5 kW for a few seconds.

These small DER technologies require power electronics to interface with the power network and its loads. There are two basic classes of microsources: DC sources, such as fuel cells, photovoltaic cells, and battery storage; and high-frequency AC sources such as microturbines, which need to be rectified. In both cases the DC voltage that is produced must be converted to AC voltage or current at the required frequency, magnitude, and phase angle. In most cases, the conversion is performed by a voltage inverter that can rapidly control the magnitude and phase of its output voltage. Fundamental frequency in an inverter is created using an internal clock that does not change as the system is loaded. This arrangement is very different from that of synchronous generators for which the inertia from spinning mass determines and maintains system frequency. Microsources, by contrast, are effectively inertia-less. As a result, basic system issues include controlling: the power feeder from the grid, the microsource's response speed, the sharing and tracking of loads among the distributed resources, the reactive power flow, the power factor, and the system's steady-state and transient stability cannot be achieved using methods developed over time for synchronous generators.

The control of inverters used to supply power from a MicroGrid to an AC system should be based on information available locally at each inverter because communication of information among many microsources is impractical. Information can be communicated among DER to enhance system performance but should not be necessary for system operation.

2.2 Combined Heat and Power (CHP)

One important potential benefit of MicroGrids is an expanded opportunity to utilize the waste heat from conversion of primary fuel to electricity. Because typically half to three-quarters of the primary energy consumed in power generation is ultimately released unutilized to the environment, the potential gains from using this heat productively are significant.

The gains of increased conversion efficiency are threefold. First, fuel costs will be reduced both because individual fuel purchases will decrease and constrained overall demand will drive down fuel prices. Second, carbon emissions will be reduced. And, third, the environmental problem of disposing of large power plant waste heat into the environment will diminish. The emergence and deployment of technologies to facilitate efficient local use of waste heat, is, therefore, key for MicroGrids to emerge as a significant contributor to the national electricity supply.

Use of waste heat in smaller-scale CHP systems is more common in many economies than in the U.S. where it is typically only found in industrial facilities. For example, in Denmark as of 1996, 48 percent of the domestic electricity demand and 38 percent of the domestic heat demand were met by CHP plants. This level of CHP contribution is believed to reduce CO₂ emissions by approximately 7-10 Mt per year, or more than 10 percent of the total CO₂ emissions of the country relative to emissions when heat and power are produced separately. Other European countries also rely on CHP to contribute significantly to power production: the Netherlands produces about 30 percent of its power from CHP systems, Germany produces about 14 percent, and Italy produces about 12 percent. In comparison, the U.S. produces only about nine percent of power from CHP.

Unlike electricity, heat, usually in the form of steam or hot water, cannot be easily or economically transported long distances, so CHP systems typically provide heat for industrial processes, on-site space heating, or local district heating. To make CHP systems viable, a sufficiently large need for heat must exist within a sufficiently dense area so that circulation of steam, hot water, or another appropriate medium is feasible and economic.

MicroGrids can capture two significant potential advantages over existing CHP systems:

1. The production of heat can move close to the point of use. In an extreme example, high-temperature fuel cells could be placed on every floor of a hospital to meet each floor's hot water needs. Because electricity is more readily transported than heat, generation of heat close to the location of the heat load will usually make more sense than generation of heat close to the electrical load. The same principle holds with large power plants, which tend to be sited close to sources of cooling water but distant from the users of their power. Because the MicroGrid permits small, diverse generators to operate in a passively coordinated manner, generators can be placed optimally in relation to loads.
2. The scale of heat production for individual units is small and therefore offers greater flexibility in matching to heat requirements. A MicroGrid should be constructed from the most economic combination of waste-heat-producing generators (e.g. high-temperature fuel cells and microturbines) and non-waste-heat producing generators [e.g. windmills or photovoltaic (PV) modules] so that the combined generation of electricity and heat is

optimized— in other words, the total cost of supplying the heat and electricity needs of the facility is minimized.

2.3 Interconnection Issues

Local interconnection standards vary considerably from one utility to the next. A national standard, ANSI standard P1547 (Draft) Standard for Distributed Resources Interconnected with Electric Power Systems is being drafted by the IEEE SC21 working group. This standard rests on certain assumptions about the contribution of DER to power quality and system reliability. Although P1547 does not use the term MicroGrid, it allows for implementation of a group of DER, which it refers to as a Local Electric Power System (LEPS). The standard applies at the point where a LEPS or MicroGrid connects to the utility and is related to the aggregate DER rating within the MicroGrid. In other words, the rules applied to a MicroGrid containing many small DER devices would be the same as for one large DER. However, the applicability of P1547 is limited to a DER rating of 10 MVA, which is larger than the ratings expected for MicroGrids.

3. MicroGrid Structure

As noted, above, the microsources of special interest for MicroGrids are small (<100-kW), low-cost, low-voltage, low-emission, highly reliable units that are aggregated with load at the customer sites. Power electronics provide the control and flexibility required by the MicroGrid concept, insuring that the MicroGrid can meet its customers' as well as the utilities' needs. These characteristics can be achieved by a system architecture that has three critical components:

- Local Microsource Controllers
- Energy Manager
- Distributed Protection Coordinator

Figure 3.1 illustrates the basic MicroGrid architecture. The electrical system is assumed to be radial with three feeders – A, B, and C – and a collection of loads. The radial system is connected to the distribution system through a separation device (e.g., a static switch). The feeders are usually 480 volts or smaller. Feeder A shows several microsources, one of which provides both power and heat. Each feeder has circuit breakers and power flow controllers. The power flow controller near the heat load in feeder A, for example, regulates feeder power flow at a level prescribed by the Energy Manager. As downstream loads change, the local microsources' power output is increased or decreased to hold the total power flow constant. In this figure, feeders A and C include microsources and are assumed to have critical loads, and feeder B is assumed to have non-critical loads that can be shed when necessary. In response to power quality problems, the MicroGrid can “island” (separate from the distribution system and operate independently) using the separation device shown in the figure. The non-critical feeder can also be dropped using the breaker at B. Islanding is discussed in more detail in Section 5.0 below.

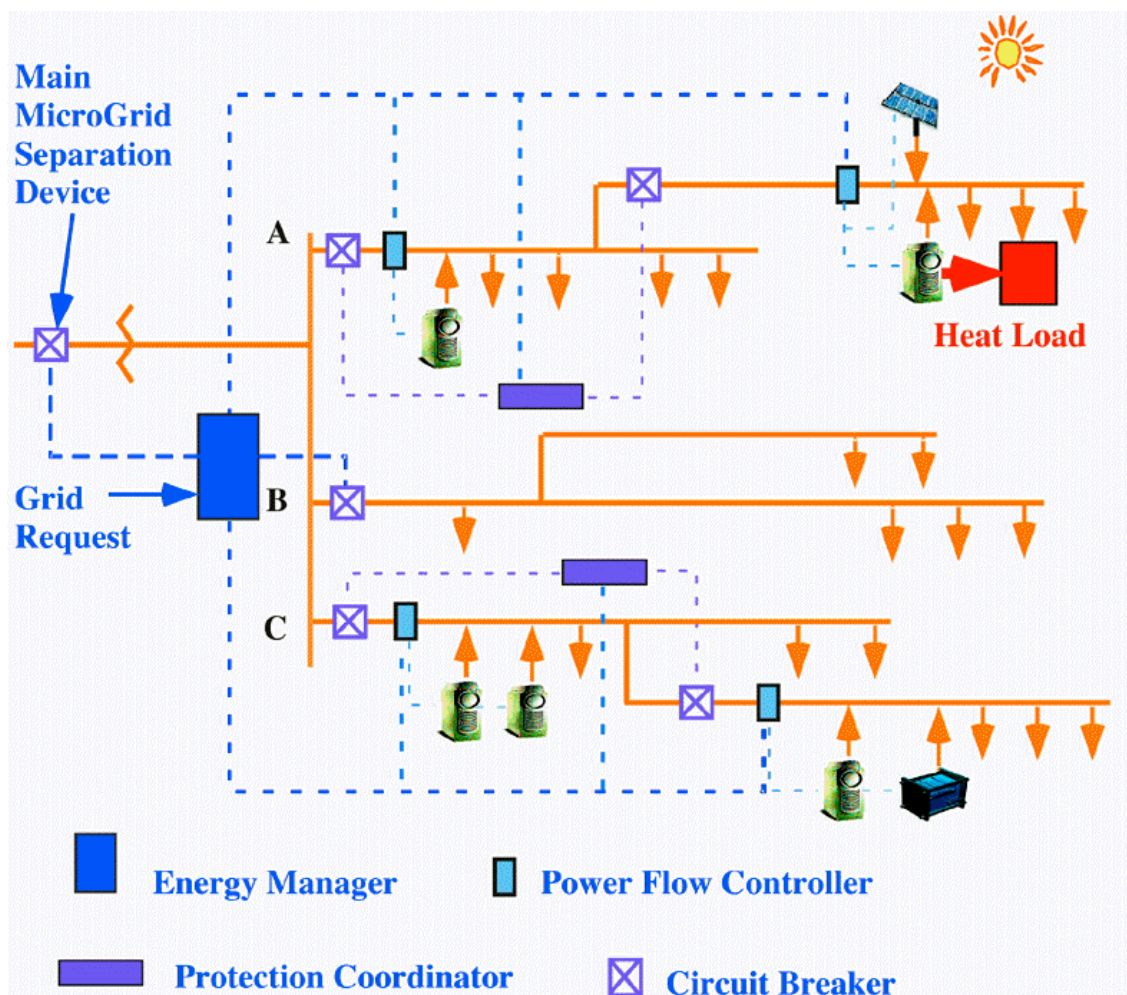


Figure 3.1 MicroGrid Architecture

MicroGrids have a layered control infrastructure with three components:

- Microsource Controller, which uses local information to control the microsource and responds in milliseconds to events;
- Energy Manager, which optimizes individual microsources to meet power supplier and customer needs by collecting system information and providing each microsource with its individual operating points (normally power and voltage set points); the time response of this function is measured in minutes;
- Protection Coordinator, which rapidly isolates feeder faults within the MicroGrid and communicates feeder status changes to the Energy Manager.

3.1 Microsource Controller

The most important component of the MicroGrid infrastructure is the local controller at each microsource. This controller responds in milliseconds and uses local information to control the microsource during all system or grid events. Communication among microsources is not

necessary for basic MicroGrid operation; each inverter is able to respond to load changes in a predetermined manner without data from other sources or locations. This arrangement enables microsources to “plug and play” – that is, microsources can be added to the MicroGrid without changes to the control and protection of units that are already part of the system. The basic inputs to the local controller are steady-state set points for output power, P , and local bus voltage, V . Section 5.0 discusses local controllers in more detail.

3.2 Energy Manager

The Energy Manager optimizes system operation using information on local electrical and heat needs, power quality requirements, electricity and gas costs, wholesale/retail service needs, special grid needs, demand- side management requests, congestion levels, etc. to determine the amount of power that the MicroGrid should draw from the distribution system. Some key Energy Manager functions are to:

- Provide the individual power and voltage set point for each power flow/microsource controller;
- Insure that heat and electrical loads are met;
- Insure that the MicroGrid satisfies operational contracts with the transmission system;
- Minimize emissions and system losses;
- Maximize the operational efficiency of the microsources; and
- Provide logic and control for islanding and reconnecting the MicroGrid during events.

3.3 Protection Coordinator

The protection coordinator must respond to both system and MicroGrid faults. If a fault is on the utility grid, the desired response may be to isolate the MicroGrid from the utility grid as rapidly as is necessary to protect MicroGrid loads. The speed at which the MicroGrid isolates from the utility grid will depend on the specific customer loads on the MicroGrid. In some cases, sag compensation can be used to protect critical loads without separation from the distribution system. If a fault occurs within the MicroGrid, the protection coordinator isolates the smallest possible section of the radial feeder to eliminate the fault. Further discussion of the functioning of the protection coordinator is found in Section 6.0 below.

3.3.1 Large Systems-Interconnected MicroGrids – Power Parks

Because a MicroGrid exploits low voltage, use of waste heat, and the flexibility of power electronics, its practical size may be limited to a few MVA (even though ANSI draft standard P1547 specifies an upper limit of 10MVA). In a large complex, loads could be divided into many controllable units e.g., among buildings or industrial sites. Each unit could be supplied by one or more MicroGrids connected through a distribution system.

For example, consider a Power Park with a total load in excess of 50 MVA. This system could be supplied from the transmission system through one or two substations using 13.8-kV underground cables. Each load group (heat and/or electrical) would be a MicroGrid connected to the 13.8-kV supply. In addition to these MicroGrids, the Power Park could employ larger generation such as one- to ten-MVA gas turbines directly connected to the 13.8-kV feeder. Each MicroGrid would be a dispatchable load. The Power Park controls would provide each MicroGrid with its load level (drawing power from the 13.8-kV feeder) while the gas turbines P and Q/V would be dispatched either locally or by the utility. The advantages of this system are that the MicroGrid structure insures greater stability and controllability, allows for a distributed command and control system, and provides redundancy to insure greater power supply reliability for the Power Park.

4. MicroGrid Presentation to the Utility Grid

MicroGrids must connect to the utility grid without compromising grid reliability or protection schemes or causing other problems, consistent with the minimal standards for all connected devices. However, MicroGrids can offer more value to the grid than simply “doing no harm.” MicroGrids can benefit the grid by reducing congestion and other threats to system adequacy if they are deployed as active, interruptible, or controlled loads that can be partially shed as necessary in response to changing grid conditions. It could also be designed to behave as an impedance load, modulated load or a dispatched load to list a few. In addition, MicroGrids could provide premium power and ancillary services, such as local voltage support.

4.1 Load as a Resource

A MicroGrid can be thought of as a controlled cell of the power system within which heat and power are generated for local customers, and generation and load are passively controlled. The MicroGrid load could be shed or dispatched from the utility power system in response to system needs, and the MicroGrid also could contract to provide predictable, firm levels of energy and ancillary services to the main grid. The MicroGrid could reduce its load on the utility grid either by raising the share it generates to meet its own loads or by reducing its load. If the value of the MicroGrid presenting itself as a dispatchable load were taken into account when MicroGrid equipment was installed, essential load-shedding capabilities could be built into the system.

Traditional load shedding has been in the form of interruptible contracts or tariffs.² Typically, a customer agrees to be curtailed up to an agreed number of times and durations. The customer's reward is either a reduced energy rate that lowers the customer's overall energy bill or a capacity and/or energy payment on the actual load being placed at risk of interruption. Usually, customers are notified by phone, fax, or mobile text messaging, when their service must be interrupted, and verification that the customer load was shed as requested takes place *ex post* based on meter data. A customer can choose not to comply with the direction to shed load although penalties are often levied and may be severe for non-compliance. A MicroGrid could easily participate in this type of load-shedding program. In some load-curtailement programs, loads are interrupted immediately and without warning. In New Zealand, for example, large numbers of loads have agreed to the installation of under-frequency relays that enable extremely rapid curtailment. A MicroGrid can participate in a similar program if it had the capability to respond by rapidly increasing its self-generation or reducing its load.

Joint, local control of generation and load is at the heart of the MicroGrid concept, which gives a particular meaning to demand-side management. Rather than controlling load for the purpose of adjusting its profile to benefit the wider power system, the MicroGrid controls generation and load together to meet the objectives of MicroGrid customers as economically as possible. The key issue for utility grid reliability is how to offer incentives to MicroGrids to invest and behave in a fashion that enhances grid reliability: e.g., real time pricing or contracts/rate discount options for load curtailment. Load shedding that takes place more rapidly than the electricity commodity market can respond to system conditions (e.g. load curtailment) is a particularly important service that the MicroGrid could offer.

4.2 Dynamic Interactions

DER are sufficiently rare at this point that their influence on the stability of the high-voltage transmission system is not an issue. However, if DER become more common, they could have a substantial influence on utility grid stability. Undesirable dynamic interactions could cause key, heavily loaded transmission lines to trip, interrupting power exports and imports between areas. However, if MicroGrids are designed with their dynamic impact on the transmission system taken into account, they can enhance the stability of transmission lines, which could permit transmission power limits to increase. The question of how much penetration of DER the grid can handle before stability problems result is not an issue with MicroGrids because they are designed so that 100 percent of their load can be handled by their microsources without creating any stability problems for the transmission system.

Key control issues that could be addressed in the design and installation of new DER are discussed in Section 5.0 below. An essential feature will be the choice of several control schemes that can be selected depending on grid operating conditions so that the MicroGrid can automatically switch to the mode that provides the greatest benefit.

² Load As a Reliability Resource in the Restructured Electricity Market. D. Kueck, B. J. Kirby, J. Eto, R. H. Staunton, C. Goldman, C. Marnay, C. Martinez. June, 2001

5. Control Methods for MicroGrids

Power electronics provide the control and flexibility for the MicroGrid to meet its customers' as well as the utilities' needs. MicroGrid controls must insure that: new microsources can be added to the system without modification of existing equipment, the MicroGrid can connect to or isolate itself from the utility grid in a rapid and seamless fashion, reactive and active power can be independently controlled, voltage sag and system imbalances can be corrected, and the MicroGrid can meet the utility's load dynamics requirements.

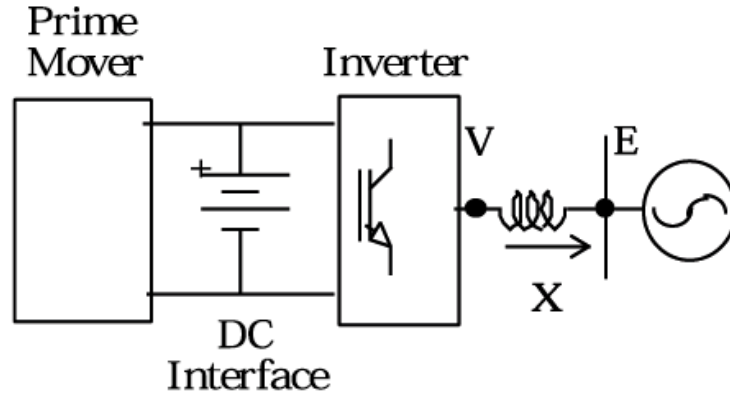
Microsource Controller techniques described below rely on the inverter interfaces found in fuel cells, photovoltaics, microturbines, and storage technologies. A key element of the control design is that communication among microsources is unnecessary for basic MicroGrid control. Each inverter must be able to respond effectively to load changes without requiring data from other sources or locations.

5.1 Microsource Control Functions

Power electronic interfaces offer control possibilities that go beyond simple control of real power, P . Basic MicroGrid control requirements are that each microsource provide:

- Control of real and reactive power,
 - Voltage regulation through droop,
 - Fast load tracking and storage, and
 - Frequency droop for power sharing.
-
- *Basic Control of Real and Reactive Power*

There are two basic classes of microsources: DC sources, such as fuel cells, photovoltaic cells, and battery storage; and high-frequency AC sources such as microturbines, which need to be rectified. In both cases the DC voltage that is produced is converted using a voltage source inverter. The general model for a microsource is shown in Figure 5.1. It contains three basic elements: prime mover, DC interface, and voltage source inverter. The microsource couples to the power system using an inductor. The voltage source inverter controls both the magnitude and phase of its output voltage, V . The vector relationship between the inverter voltage, V , and the system voltage, E , along with the inductor's reactance, X , determines the flow of real and reactive power (P & Q) from the microsource to the system.



• **Figure 5.1 Interface Inverter System**

The P & Q magnitudes are coupled as shown in the equations below. For small changes, P is predominantly dependent on the power angle, δ_p , and Q is dependent on the magnitude of the inverter's voltage, V. These relationships constitute a basic feedback loop for the control of output power and bus voltage, E, through regulation of reactive power flow.

$$P = \frac{3}{2} \frac{VE}{X} \sin \delta_p$$

$$Q = \frac{3}{2} \frac{V}{X} (V - E \cos \delta_p)$$

$$\delta_p = \delta_V - \delta_E$$

• **Voltage Regulation through Droop**

Integration of large numbers of microsources into a MicroGrid is not possible with basic P-Q controls; voltage regulation is necessary for local reliability and stability. Without local voltage control, systems with high penetrations of microsources could experience voltage and/or reactive power oscillations. Voltage control must insure that there are no large circulating reactive currents between sources. The issues are identical to those involved in control of large synchronous generators. In the power grid, the impedance between generators is usually large enough to greatly reduce the possibility of circulating currents. However, in a MicroGrid, which is typically radial, the problem of large circulating reactive currents is immense. With small errors in voltage set points, the circulating current can exceed the ratings of the microsources. This situation requires a voltage vs. reactive current droop controller so that, as the reactive current generated by the microsource becomes more capacitive, the local voltage set point is reduced. Conversely, as the current becomes more inductive, the voltage set point is increased. The function of the basic controller is shown in Figure 5.2. The Q limit shown in the figure is a function of the volts-ampere (VA) rating of the inverter and the power provided by the prime mover.

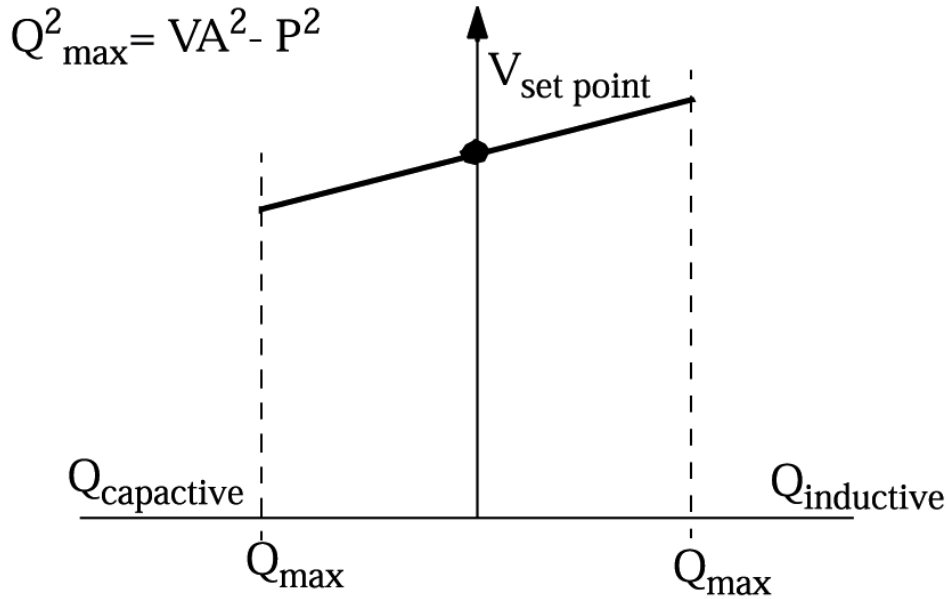


Figure 5.2 Voltage Set Point with Droop

- **Fast Load Tracking and the Need for Storage**

A MicroGrid with clusters of microsources and storage could be designed to operate both in isolation and connected to the power grid. When the MicroGrid operates in isolation, load-tracking problems will arise because microturbines and fuel cells respond slowly (time constants range from 10 to 200 seconds) and are inertia-less. Utility power systems currently have storage in the form of generators' inertia. When a new load comes on line, the initial energy balance is satisfied by the system's inertia, which results in a slight reduction in system frequency. A MicroGrid cannot rely on generators' inertia and must provide some form of storage to insure initial energy balance.

MicroGrid storage can come in several forms: batteries or supercapacitors on the DC bus for each microsource; direct connection of AC storage devices (batteries, flywheels etc.); or use of traditional generation with inertia along with microsource generators. If the MicroGrid is not required to operate in island mode, the energy imbalance can be met by the AC system, and storage on the MicroGrid is not necessary.

- ***Frequency Droop for Power Sharing (in Islanded Mode of Operation)***

MicroGrids provide premium power because they can move smoothly move from dispatched power mode (while connected to the utility grid) to load tracking (while in island mode). In island mode, problems such as slight errors in frequency generation at each inverter and the need to change power-operating points to match load changes must be addressed. Power vs. frequency droop functions at each microsource can take care of the problems without the need for a complex communication network.

When the MicroGrid is connected to the utility grid, MicroGrid loads receive power both from the grid and from microsources, depending on the customer's situation. If utility grid power is lost because of voltage drops, faults, blackouts, etc., the MicroGrid can transfer smoothly to island operation. When the MicroGrid separates from the utility grid, the voltage phase angles at each microsource in the MicroGrid change, resulting in an apparent reduction in local frequency. This frequency reduction coupled with a power increase allows for each microsource to provide its proportional share of load without new power dispatch from the Energy Manager. In fact, the Energy Manager is not used in island operation except at the time of reconnection to the utility grid.

Consider two microsources as in Figure 5.3. In this example, the sources are assumed to have different ratings, P_{1max} , and P_{2max} . The dispatched power in grid mode (P_{01} and P_{02}) is defined at base frequency, ω_0 . The droop is defined to insure that both systems are at rated power at the same minimum frequency.

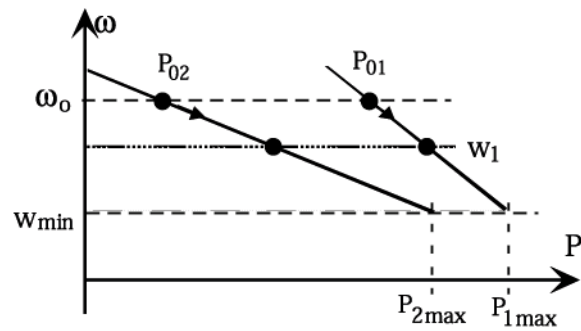


Figure 5.3 Power vs. Frequency Droop Control

During a change in power demand, these two sources operate at different frequencies, which causes a change in the relative power angles between them. When this change occurs, the two frequencies tend to drift toward a lower, single value for ω_1 . Unit 2 was initially operating at a lower power level than Unit 1. However, at the new power level, Unit 2 has increased its share of the total power needs. Although power is adjusted within fractions of a second, frequency restoration can take longer. Because droop regulation decreases the MicroGrid frequency a restoration function must be included in each controller. Droop control design is based on each microsource having a maximum power rating. As a consequence, droop is dependent on the dispatched power level while the microsources are connected to the grid.

5.2 Example System

An industrial plant with high motor loads can be used to illustrate the dynamics of the MicroGrid controls presented in the previous section. This industrial site has nearly 1.6 MW of motor load with motors ranging from 50 to 150 hp each; there are also two large synchronous machines. A 120-kV line provides power through a long 13.8-kV feeder consisting of overhead lines and underground cables. The plant has three main feeders; two at 480V and one at 2.4kV. The loads on the 480-V feeders are critical and must continue to be served if utility power is lost.

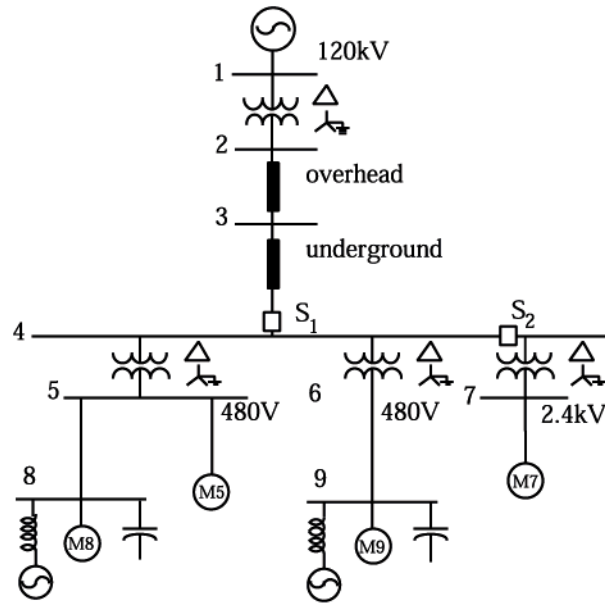


Figure 5.4 Example System, One-Line

Details of the plant are shown in Figure 5.4. The induction machine clusters (M8 and M9) are connected to buses 8 and 9 with capacitive voltage support. Two clusters of microsources are also connected to buses 8 and 9 to provide power and voltage support. In the absence of locally generated power, the voltages of buses 8 and 9 are 0.933 and 0.941 per unit (pu, on 480-V base) respectively. Total losses are 70 kW. Each cluster of microsources is rated at 600 KVA and provides both power injection and local voltage support. The microsource power injection is approximately one half the total power. With these sources operating, the voltages on buses 8 and 9 are regulated at 1 pu, and the total losses drop to 6kW, a reduction of 64kW. Simulation of grid-connected operation is shown in Figures 5.5 and 5.6. In the initial state, local sources are not generating power, so Figure 5.5 shows zero real and reactive power injection and reduced voltages on buses 8 and 9. At $t = \text{one second}$, the generators at bus 8 are brought on line with a power setting of 446 kW and local voltage control. Note the voltage correction in Figure 5.6(a).

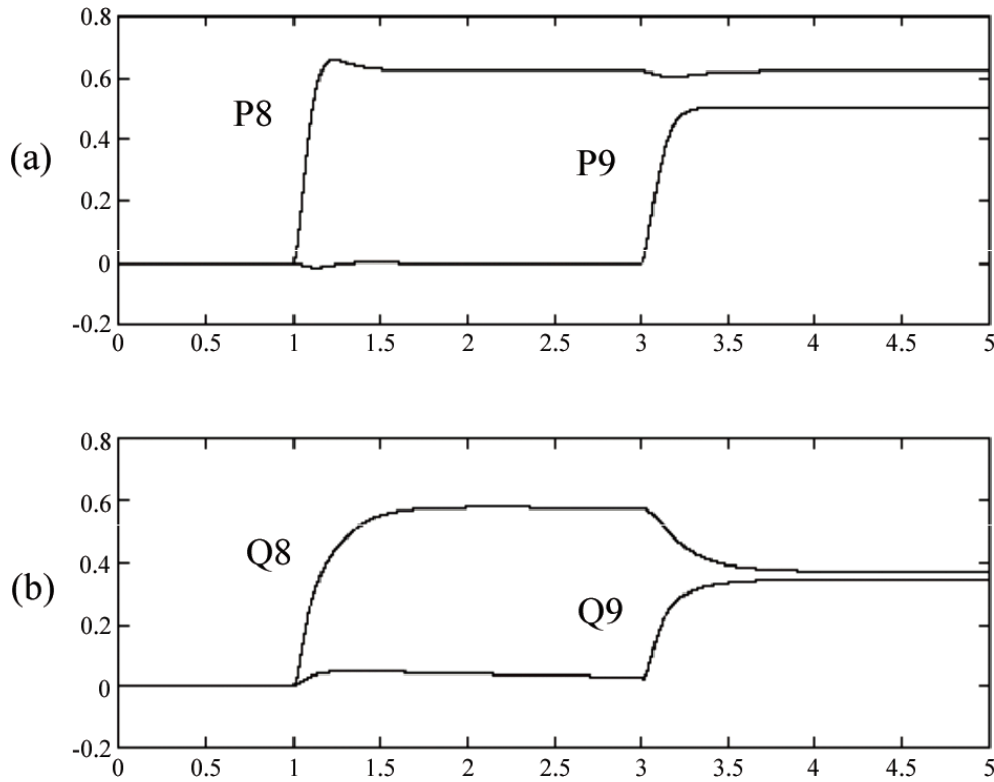


Figure 5.5 Start-up P & Q of Microsources in Grid-Connected Mode (a) Active Power pu, (b) Reactive Power pu

At $t = 3$ seconds, the units at bus 9 are brought on line with a power set point of 360 kW and local voltage control. Figure 5.5 shows the active and reactive power injections at the buses where units are located. As the second microsource is brought on line, the Q injection at bus 8 to maintain local voltage magnitude drops. Figure 5.6 shows half of the voltage envelope at the regulated buses during the start-up sequence. Voltage on bus 9 is controlled to 1 pu within a few cycles.

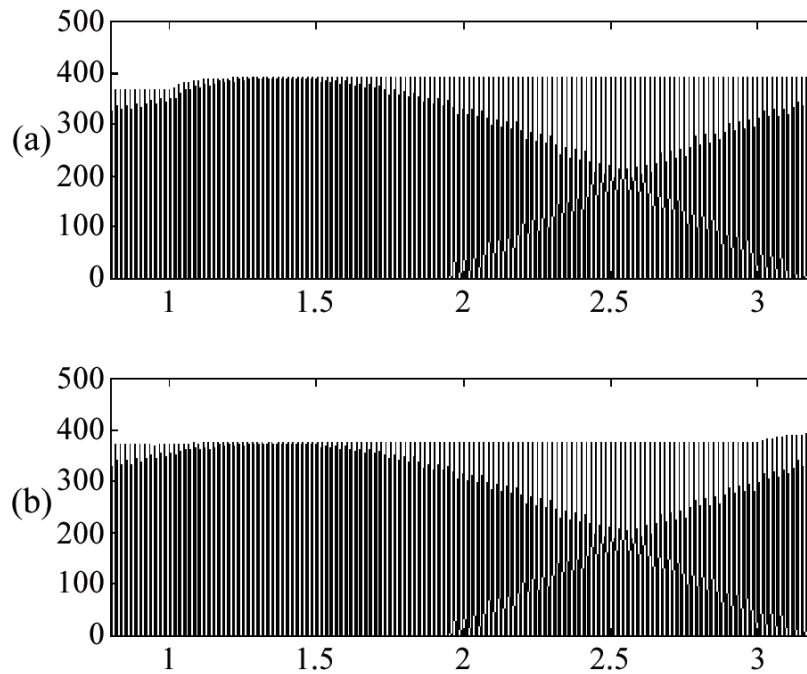


Figure 5.6 Regulated voltage (a) bus 8 (b) bus 9

This example can also be used to simulate island operation with power sharing through droop. It is assumed that the ratings of the microsources are not adequate to supply the total load. The two 480-V feeders supply critical loads, and the M7 load on bus 7 can be dropped using breaker S_2 (see Figure 5.4)

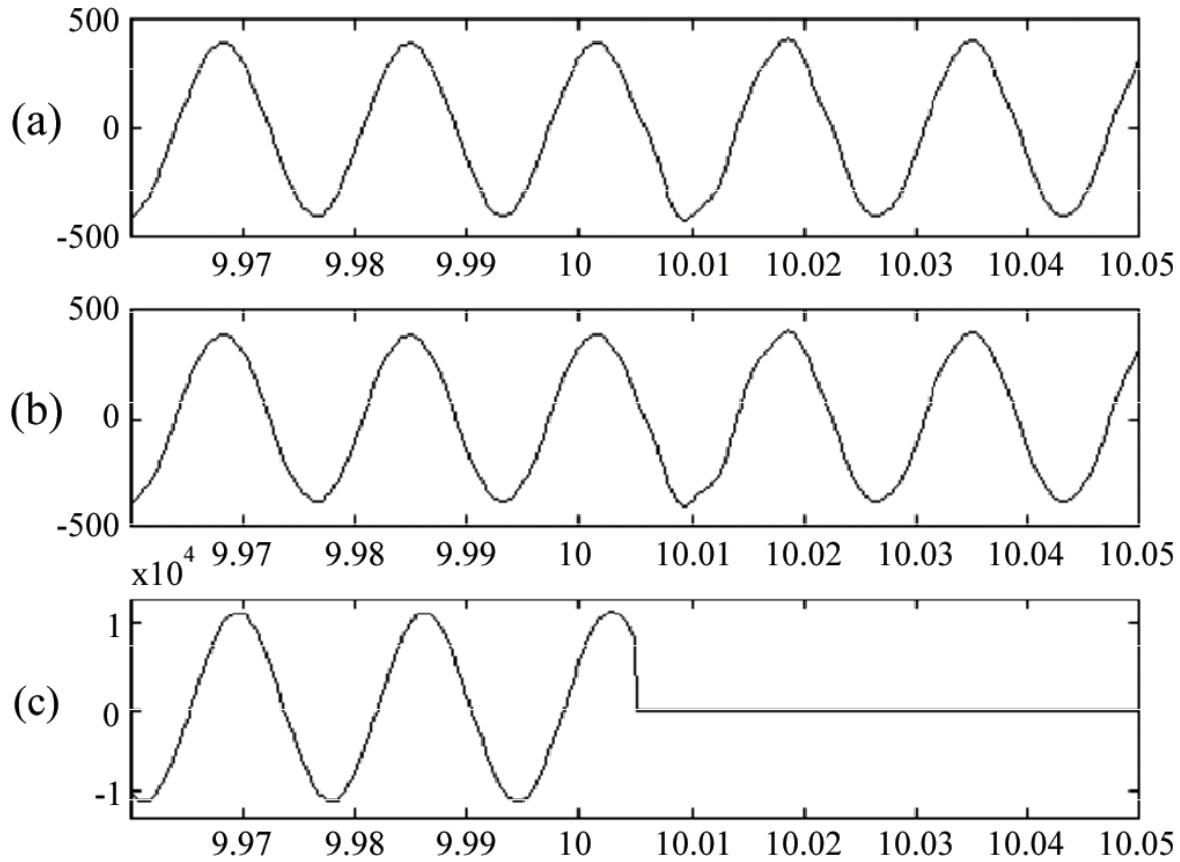


Figure 5.7 Regulated voltages during transfer to island operation (a) bus 8 (b) bus 9 (c) 13.8-kV feeder

At $t=10$ seconds, the system moves from grid-connected to island operation by the tripping of switch S_1 in response to supply problems (Figure 5.7c). At the same time, the non-critical feeder is dropped using S_2 . Waveforms for bus 8 and 9 voltages during the switch to island mode are shown in Figures 5.7(a)-(b). There is only a slight change from the sinusoidal steady state; the change lasts less than a cycle.

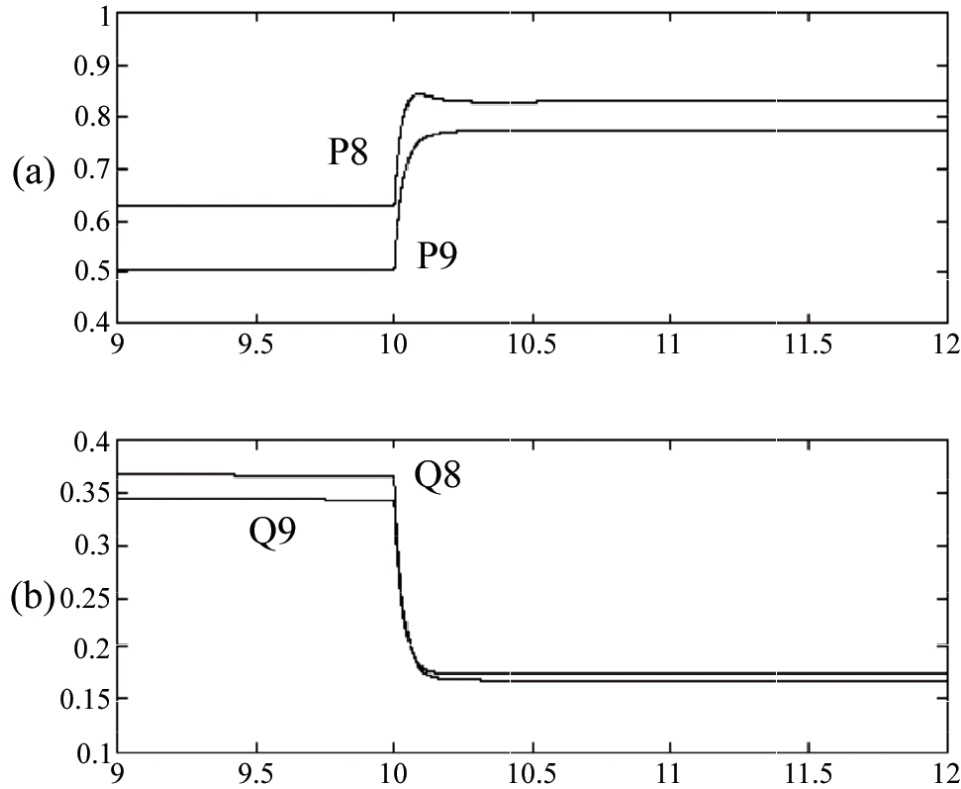


Figure 5.8 P&Q Transient during Transition from Grid-Connected to Island Operation

Figure 5.8 shows the changes in active and reactive power during the transition. Active power has to take up the critical load in the absence of grid power. Both machine clusters increase their power injection as expected from the design of the droop characteristics. The machine with lighter load (Figure 5.3.) at bus 9 picks up the largest part of the new load demands, as seen in Figure 5.8(a). Reactive power injection reduces but holds the voltages at 1 pu. Power regulation takes place very rapidly, and steady-state power is restored in less than one second. The system frequency droops a little more than 1 Hz. Meanwhile, the frequency restoration loop has started and restores the frequency to 60 Hz.

6. Protective Relaying and MicroGrids

The protective relay design for MicroGrids must be different from what has historically been used for utility distribution systems because MicroGrids add a significant number of electrical sources to a customer's system, which has historically contained only loads. Some of the differences resulting from this change are obvious; for example, once sources are added, energy can flow in either direction through protection system sensing devices. There are no two-directional flows on most radial systems. A more subtle difference between MicroGrids and traditional utility distribution grids is that MicroGrids will experience a significant change in short circuit capability when they switch from grid-connected to island operation. This change in short circuit capability will have a profound impact on the vast majority of protection schemes used in today's systems, which are based on short-circuit current sensing.

The protection issues that must be resolved for MicroGrids will be discussed in two scenarios:

1. The first scenario is “normal” operation, in which the MicroGrid is connected to the utility grid when a grid event occurs. The protection system must determine the response of the individual DER that make up the MicroGrid as well as the response of the device that will disconnect the MicroGrid from the utility grid and switch it to islanded operation. This device is labeled “Main MicroGrid separation device” in Figure 6.1. (Figure 6.1 is a version of Figure 3.1 that is modified to highlight protection issues).
2. The second scenario involves an event on the MicroGrid while the MicroGrid is in island operation mode.

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6.1 Events Occurring During Normal Operation

“Normal operation” in this context means that the MicroGrid is connected to the utility grid (i.e., the main MicroGrid separation device, indicated in Figure 6.1, is closed.) The issues addressed in this operational scenario are the responses of the individual DER and the entire MicroGrid to events on the utility grid and to events within the MicroGrid.

The appropriate response to an event on the utility grid will vary depending on the requirements of the MicroGrid loads. For example, if the MicroGrid loads are mainly retail enterprises, the main concern will be to keep the lights on so that the businesses can continue serving customers. Any sensitive loads, such as computers associated with cash registers and inventory control, should have dedicated uninterruptible power supply (UPS) systems so that a brief outage (i.e., several seconds) will not affect the enterprise’s capacity to continue with business as usual.

If the businesses in the MicroGrid include sensitive loads such as those that are part of many manufacturing lines, the outage times that can be tolerated may be significantly smaller than in the retail customer example above. This is particularly true if the businesses in question participate in the MicroGrid expressly because it provides reliable power supply and thus these customers have not invested in UPSs. If these businesses include semiconductor manufacturers, their equipment may meet the SEMI F47 standard, which has very tight voltage tolerance requirements. These customers will have high expectations of reliability from a MicroGrid.

- **Events on the Utility Grid**

The desired response to many events on the utility grid will be to isolate the MicroGrid as rapidly as is necessary to protect MicroGrid loads. As noted above, the rapidity with which isolation must be accomplished to avoid disruption to customers depends on the specific loads on the MicroGrid.

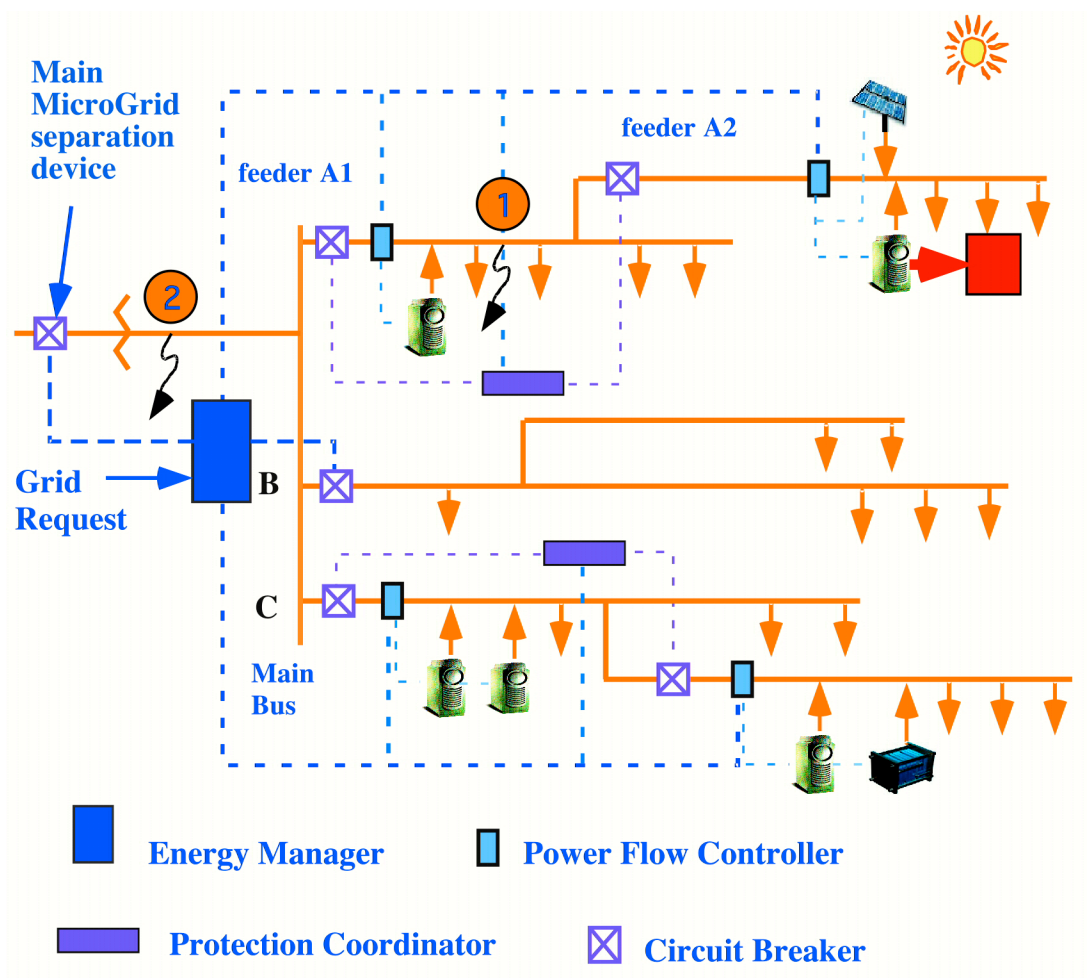


Figure 6.1. Faults on the MicroGrid

The high-speed fault interruption device that is necessary to disconnect the MicroGrid is noted in Figure 6.1 as the main MicroGrid Separation Device. Depending on the voltage class, the speed of operation required, and the fault current availability, this device may vary from a molded-case circuit breaker with shunt trip to a high-speed static switch. In all cases, a protection scheme will need to be designed for the characteristics of the specific interconnection so that the MicroGrid separation device will trip as needed. This scheme may be relatively simple, such as monitoring current magnitude and direction on each phase and sending a trip signal to the separation device if preset limits are exceeded, or it may be a relatively complex scheme that monitors waveform and attempts to achieve the much-discussed quarter-cycle trip time.

The individual DER in the above scenario must have protection schemes that enable them to continue to operate while the sensing and switching takes place that will disconnect the MicroGrid from the utility grid. That is, the event should not trip the DER until the protection scheme has had a chance to separate the MicroGrid from the utility grid. If the fault remains on the MicroGrid once the MicroGrid is disconnected, and the event is determined not to be on the utility grid, a second set of protective decisions must be made, which will be discussed below.

Nuisance (avoidable) separations must also be considered. They will not usually result in loss of load to MicroGrid customers, but they can result in increased costs because of increased operation of the MicroGrid separation device (which will reduce its lifetimes) and increased labor to restore normal operations. The current draft of IEEE standard P1574 requires separation for certain voltage and frequency perturbations. These requirements are being carefully scrutinized to ensure that adequate protection is provided and nuisance trips are minimized.

- **Events on the MicroGrid While Connected to the Main Utility**

From the perspective of the individual DER and individual MicroGrid loads, there is no way to distinguish between an event that occurs on the feeder supplying the MicroGrid that is on the utility side of the MicroGrid disconnecting device and an event that is on the MicroGrid side of this device, as indicated by “Fault 1” on Figure 6.1. However, the responses to these two events should be different. As discussed above, the response to the event on the utility side of this device should be to separate the MicroGrid from the main utility and maintain normal MicroGrid operation. Note that “maintain normal operation” means keeping loads functional; to accomplish this, the DER control method may need to be altered from the method used while the MicroGrid is grid connected in order to account for the significantly “softer” MicroGrid operation in the absence of utility grid support. This altered control is discussed in section 5.0.

The response to an event on the MicroGrid side of the separation device will include opening the separation device in addition to taking appropriate isolation measures within the MicroGrid. For example, Fault A in Figure 6.1 would require opening of the MicroGrid separation device as well as opening the three circuit breakers connected to the main bus. Fault 2 would require opening the breakers protecting feeders A1 and A2.

In the case of a fault within the MicroGrid, separation from the utility grid should be timed to coordinate with the protection “upstream” (in the direction of the utility source) from the main MicroGrid separation device. This coordination will depend on the protection philosophy of the interconnecting utility. Typical coordination might require that the MicroGrid separation device trip before any upstream device trips, to minimize the number of customers affected by a particular event. Note that the time required to open the separation device in this case may be different than the time required to open the same device in response to an event on the utility side.

In addition to the opening of the MicroGrid separation device, it will be necessary to isolate from the rest of the MicroGrid the line segment within the MicroGrid that contains the event, as discussed above for Fault 2. How this is accomplished will depend on the features and complexity of the MicroGrid. The basic responses of protective devices within the MicroGrid will be the same as those discussed below for the isolated MicroGrid.

- **Resynchronization**

Finally, once service has been restored to the utility grid after an event has caused separation of the MicroGrid from the utility grid, the MicroGrid must have the means to synchronize and reconnect with the utility grid. Ideally, this should take place as soon as the utility grid has had

an opportunity to pick up all previously disconnected loads and to stabilize, which may require several seconds to several minutes, depending on the nature of the feeder and loads. The MicroGrid Energy Manager must have a control scheme that can bring all DER on the MicroGrid into synchronization with the main utility, based on measuring the voltage on both sides of the separation device. Whether this resynchronization and reconnection are done automatically or manually may vary depending on the characteristics of the MicroGrid and the interconnecting utility. Resynchronization philosophies and techniques must be studied to determine appropriate approaches.

6.2 Events on the Isolated MicroGrid

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Consider, as discussed in the preceding section, an event that occurs on the MicroGrid side of the MicroGrid separation device, as shown by Fault 1 in Figure 6.1. The MicroGrid separation device will be required to open in these circumstances, and timing will need to be coordinated with upstream devices.

Responses will also be required from devices within the MicroGrid because the MicroGrid contains sources that can maintain a fault. The response of protective devices within the MicroGrid will vary dramatically depending on the complexity of the MicroGrid. An isolated MicroGrid that contains only one source may be able to employ a protection scheme similar to that used on a conventional radial distribution system. More complex MicroGrids with a number of DER will require more complex protection schemes. Decisions about the cost and complexity of protection schemes will depend on the needs of the MicroGrid customers.

For a MicroGrid in which customers each have adequate DER to serve their own energy needs, protection can be simple: customers can each isolate themselves from the remainder of the MicroGrid in response to an event. However, this protection scenario fails to take advantage of the diversity of load and generation that is possible in a MicroGrid. An approach that more effectively shares the resources of a MicroGrid will necessarily require more complex protection. Fault 2 in Figure 6.1, for example, will require that the circuit breakers for Feeders A1 and A2 trip. As a result, the loads on Feeder A1 will not be served (this is unavoidable without individual load UPSs) while those on Feeder A2 will remain active. However, the method for detecting Fault 2 is not as straightforward as it might seem because of the dramatically reduced short-circuit current available on the isolated MicroGrid, as will be discussed in the next subsection.

- **Reduced Short-Circuit Current Availability**

When a fault occurs on the isolated MicroGrid, the MicroGrid's reduced short-circuit current capability has a significant impact. When the MicroGrid is connected to the utility grid, the utility source could provide fault current that is orders of magnitude greater than load current. This high fault current is easily distinguished from load current and thus is conventionally used to detect faults on radial distribution systems.

Most conventional distribution protection is based on short-circuit current sensing. There is a large class of DER – including fuel cells, many microturbines, photovoltaic systems, many wind

systems, and battery energy storage systems – that uses inverters to interface with the utility grid. This class of DER may be capable of supplying only twice the load current or less to a fault, so the orders-of-magnitude larger fault current on which conventional overcurrent protection is based is not present. Some overcurrent sensing devices will not even respond to this small amount of overcurrent; those that do respond will take many seconds to do so rather than the fraction of a second that is required. Thus, alternate means of detecting an event must be adopted. There are alternate means available, such as the use of impedance, or ground current relaying. The application of these techniques to distribution and customer systems is not as well understood as overcurrent sensing protection schemes.

7. MicroGrid Economics

The economics or business case for the MicroGrid determines the configuration and operation of the MicroGrid. Issues of MicroGrid economics can be roughly divided into three categories:

1. The first concerns the basic economics of optimal investment and operation of technologies available to the MicroGrid. These are problems that, at least at the utility scale, have received intense academic scrutiny; as a result, established and reliable tools are available to guide decision making and should, with some adaptation to the specifics of MicroGrids, be effective.
2. The second concerns some of the unique aspects of MicroGrids that will require innovation. In general, these are areas in which MicroGrids differ significantly from distribution systems, for example, the possibility of providing heterogeneous levels of reliability to various end uses, and the critical central importance of some operational constraints, such as noise, that are relatively insignificant to utility economics.
3. The third concerns the relationship of the MicroGrid to the distribution system. In many ways these problems resemble familiar ones related to the interface between customers and utilities, for example, the need to provide a real-time price signal to the MicroGrid so that optimal use of resources by both the MicroGrid and utility can be achieved simultaneously. Other problems are more novel and challenging. For example, MicroGrids' ability to participate in grid-scale ancillary services markets will most likely be limited by voltage and losses, but MicroGrids could still provide some local services, such as voltage support. Creating a market for localized voltage support, or even placing meaningful value on it, seems unlikely at the present time.

7.1 MicroGrids and Traditional Power System Economics

A MicroGrid is designed, installed, and operated by a customer or group of customers primarily for their economic benefit. Although MicroGrid participants may be concerned about the environmental effects of their energy supply system as well as about noise and other similar considerations, the most important benefit that participants seek is a lower total energy bill (i.e., combined bill for heat, electricity, and transportation). The MicroGrid may be able to operate some or all of its end uses at lower cost than would be possible on the utility system. The cost of delivered energy from the traditional power system includes losses, customer services, congestion, and other costs that together typically exceed the generation (bus bar) cost alone.

The MicroGrid will likely have smaller losses as well as other advantages that will lower its costs relative to the costs of the distribution system.

Table 1 shows present-day cost information for some small-scale generating technologies currently available for deployment in MicroGrids. Table 2 shows forecasts of these costs for 2010. The first notable feature of Table 1 costs is that on-site generation is currently competitive with central station generation at certain times and in certain places. However, the currently available technology that is apparently cheapest, reciprocating engines, has some pronounced disadvantages, notably air quality impacts (and the associated difficulty of getting related permits), noise, and interconnection costs. During the coming decade, costs of other, new technologies are likely to fall significantly, so that, by 2010, another option, fuel cells for example, may be the cheapest on-site generating technology available under some circumstances. Fuel cells and other types of DER have fewer disadvantages than reciprocating engines. Even without consideration of other benefits of DER, their economics suggest that they will challenge the economies of scale that originally motivated reliance on traditional central station generation.

• **Table 1**

	Name	DER Type	Source	Nameplate kW	lifetime (a)	\$/kW cost FOB cost	\$/kW cost Turnkey cost	OMFix \$/kW/a	OMVar \$/kWh	Lev Cost c/kWh	Heat Rate kJ/kWh
1	MTL-C-30	MT	SCE	30	12.5	1200	1333	119	in Fix O&M	12.14	12,186
2	PAFC-O-200	PAFC	TAG	200	12.5	3500	PR	PR	PR	13.68	PR
3	DE-K-30	Diesel Backup	manufacturer	30	12.5	473	1290	26.5	0.000033	5.51	11,887
4	DE-K-60	Diesel Backup	manufacturer	60	12.5	290	864	26.5	0.000033	6.30	11,201
5	DE-K-500	Diesel Backup	manufacturer	500	12.5	166	386	26.5	0.000033	4.65	10,314
6	DE-C-7	Diesel Backup	manufacturer	7.5	12.5	213	627	26.5	0.000033	N/A	10,458
7	DE-C-200	Diesel Backup	manufacturer	200	12.5	135	416	26.5	0.000033	4.94	9,944
8	GA-K-55	Gas Backup	manufacturer	55	12.5	290	970	26.5	0.000033	7.55	12,997
9	GA-K-500	Gas Backup	manufacturer	500	12.5	408	936	26.5	0.000033	7.33	12,003
10	WD-10	Wind	Bergey Windpower	10	12.5	2805	6055	5.7	0	27.05	
11	PV-5	PV	Jeff Oldman, Real Goods	5	20	7150	8650	14.3	0	55.23	
12	PV-50	PV	Jeff Oldman, Real Goods	50	20	5175	6675	5	0	42.62	
13	PV-100	PV	Jeff Oldman, Real Goods	100	20	5175	6675	2.85	0	42.62	

Table 2

	Name	DER Tech Type	Source	Plate kW	lifetime (a)	\$/kW cost FOB cost	\$/kW cost Turnkey cost	OMFix \$/kW/a	OMVar \$/kWh	Lev Cost c/kWh	Heat Rate kJ/kWh
1	MTL-C-30	MT	SCE	30	12.5	1200	1333	119	in Fix O&M	12.14	12,186
2	PAFC-O-200	PAFC	TAG	200	12.5	1300	PR	PR	PR	10.15	9,480
3	PAFC-O-1200	PAFC	TAG	1200	12.5	1300	PR	PR	PR	8.14	9,080
4	SOFC-SW-3100	SOFC-CT	TAG	3100	12.5	600	PR	PR	PR	7.66	6,153
5	PEM-BA-250	PEM-FC	TAG	250	12.5	710	PR	PR	PR	8.68	9,154
6	SOFC-C8-500	SOFC	TAG	500	12.5	750	PR	PR	PR	8.97	6,692
7	PEM-25kW	PEM-FC	Ogden & Kreutz	25	12.5	976	1000	4	0.0007	11.75	10,800
8	PEM-50kW	PEM-FC	Ogden & Kreutz	50	12.5	786	800	2	0.0006	7.70	10,800
9	FCV-75	FCV-75	Tim Lipman	30	12.5	0	83	20	0.029000	7.75	9,231
10	DE-K-30	Diesel Backup	manufacturer	30	12.5	473	1260	27	0.000033	5.51	11,887
11	DE-K-60	Diesel Backup	manufacturer	60	12.5	290	864	27	0.000033	6.30	11,201
12	DE-K-500	Diesel Backup	manufacturer	500	12.5	166	386	27	0.000033	4.65	10,314
13	DE-C-7	Diesel Backup	manufacturer	7.5	12.5	213	627	27	0.000033	N/A	10,458
15	DE-C-200	Diesel Backup	manufacturer	200	12.5	135	416	27	0.000033	4.94	9,944
17	GA-K-55	Gas Backup	manufacturer	55	12.5	290	866	27	0.000033	7.55	12,997
18	GA-K-500	Gas Backup	manufacturer	500	12.5	408	936	27	0.000033	7.33	12,003
19	WD-10	Wind	Bergey Windpower	10	12.5	2805	6055	6	0	27.05	
20	PV-5	PV	Jeff Oldman, Real Good	5	20	3580	5080	14	0	32.43	
21	PV-50	PV	Jeff Oldman, Real Good	50	20	2588	4088	5	0	26.10	
22	PV-100	PV	Jeff Oldman, Real Good	100	20	2588	4088	3	0	26.10	

Straightforward application of engineering-economic principles can help determine which technologies are likely to be attractive to MicroGrids and how these technologies will be deployed and operated. In many regards, the economics of MicroGrids are similar to those of utility-scale systems. For example, the rules of economic dispatch apply to both, and minimizing costs for both types of systems requires that the lowest-possible-cost combination of resources must be operating at all times, to the extent that equipment characteristics allow. Purchase and sale of electricity is possible in both utility-scale and MicroGrid systems, and both of these activities may occur at different times. The variety of duty cycles required implies that the optimal combination of resources chosen by the MicroGrid will be technologically diverse, like the combinations used in utilities. In this context, technologically diverse resources include those used to meet a range of demands: baseload duty-cycle needs, peak demand, and others degrees of demand between these two extremes. Different types of generators will be most efficient at meeting different types of demand. The classic solution in utility systems is that high-capital, low-variable-cost technologies are suitable for the baseload, and generators with the opposite qualities are suitable for peak demand; this principle could prove equally true for MicroGrids.

Although there are numerous similarities between MicroGrid and utility economics, some aspects of traditional MicroGrid economics are novel and will require rethinking or extending familiar tools. Two notable examples are joint optimization of heat and power supply and joint optimization of loads and supply.

CHP is a relatively underdeveloped area of power system economics. Use of CHP is common in U.S. industry, and about nine percent of U.S. electricity is currently generated in CHP systems. A major non-industrial application is district-heating systems, which are extensively used in some northern European cities, such as Warsaw. However, these systems have tended to develop in response to isolated opportunities for use of waste heat; until recently, use of heat was not one of the central objectives of utility-scale power system development. A key reason for current rethinking of this issue is the drive to reduce carbon emissions. Increasing the overall efficiency of power generation in the U.S. from the expected approximately 33 percent in 2010 to

approximately 70 percent could, without fuel switching, provide one half of the 28 percent (approximately 500 Tt) overall reduction in total U.S. carbon emissions suggested by the Kyoto Protocol for that year. CHP is the only approach that could deliver power generation efficiency improvements of this magnitude.

As a consequence of the scant historic interest in CHP, utility systems have tended to place generation stations close to convenient cooling resources rather than at locations that would facilitate use of waste heat. Because one of the driving forces for MicroGrids is the desire to move power generation toward using waste heat, CHP will likely be at the heart of MicroGrid economics.

There are three immediately apparent potential applications of CHP in MicroGrids:

1. Space heating, domestic hot water heating, and sterilization;
2. Industrial or manufacturing processes; and
3. Space cooling and refrigeration through use of absorption chilling.

To show that the attraction of exploiting CHP opportunities will be a key motivator for customers to self-generate electricity, it is sufficient to show technically feasible examples in which CHP applications of any of the three types can lower the joint cost of providing electricity and heat/cooling relative to the cost of providing these services from separate purchased sources (typically purchased power and natural gas come from local utility systems). To show that CHP alone is a strong motivator for multiple customers to join together and form MicroGrids, it is also necessary to show that aggregation of heat and power loads has economic benefits. It is not difficult to see that this would be true in certain cases, e.g. a bottling plant with modest space heat and large sterilization loads might optimally produce more electricity than it can by itself consume and would benefit by being part of a MicroGrid. However, a full economic case has not yet been made regarding the degree to which CHP opportunities will motivate customers to form MicroGrids.

Joint optimization of demand and supply is a second, key area where some extension of traditional power system economics is required for MicroGrids. In utility-scale systems, control of loads is usually addressed during analysis and planning as demand-side management (DSM), load control, or load shedding and interruptible tariffs or contracts. MicroGrids are different in a number of key respects. First and most importantly, the marginal cost of self-generation at any point in time is well known to and actually paid by the MicroGrid. In other words, the vagaries of investment cost recovery, cross subsidies, and inaccurate metering and tariffs are all avoided. The generator and consumer are the same decision maker, and the struggle to coordinate investment and operating decisions on what were formally thought of as opposite sides of the meter is eliminated. The MicroGrid can readily know both its marginal cost of providing power at any point in time and the equivalent costs of investments in energy efficiency, and can, with some introspection and analysis, decide what its cost of curtailment is and then can readily trade off the three. This simple reality elevates load control to a new level of importance in MicroGrids and requires an extension of current thinking.

7.2 Newer Economic Issues in MicroGrids

The second group of economic issues related to MicroGrids covers some unique MicroGrid features that require innovation in traditional power system economics. In general, these are areas in which MicroGrids differ significantly from utility systems, for example, the possibility of providing heterogeneous levels of reliability to various end uses within the MicroGrid, and the central importance of some operational constraints, such as noise, that are relatively insignificant to utility economics.

Utility-scale power systems have traditionally been designed and operated around the concept of “universal service,” which holds that the quality and reliability of power delivered to all customers must meet roughly the same standard. In practice, there are significant deviations from this universal standard, in part because of the problems of serving vast and diverse geographic areas, but the goal is still to adhere to a universal standard. A key motivation of MicroGrids is the desire to move control of power reliability and quality closer to the point of end use so that these properties can be optimized for the specific loads served. Simple economics tells us that tailoring power reliability and quality to the end uses served can deliver benefits simply because, in times of energy shortfall, energy can be moved from lower value end uses to higher value ones. Also, given that providing higher quality and reliability can be assumed to entail some cost, savings will result if higher quality power is not provided to end uses for which it is not required. Traditional power system economics has paid considerable attention to some aspects of valuing power quality and reliability, notably to estimating the cost of general outages and to schemes of priority pricing that would allow customers to exercise choice in their level of reliability; however, the notion that systems could be built around heterogeneous service quality is a quite new. Another related issue (addressed in more detail below) concerns the optimal level of quality for the universal service provided by the utility. If widespread MicroGrids effectively serve sensitive loads with locally controlled generation, back-up, and storage, the bulk power system benefits because it is no longer constrained to set its reliability requirements to meet the needs of sensitive local end uses.

7.3 Economic Issues Between MicroGrids and the Utility Systems

The third set of economic questions related to MicroGrids covers the relationship of MicroGrids to the utility. A fundamental tenet of the MicroGrid paradigm is that the MicroGrid must represent itself to the utility as a good citizen; that is, it must adhere strictly to the rules that apply to all connected devices. The MicroGrid must behave as a legitimate customer or generator or both, and may enhance those traditional economic roles.

Delivering true price signals in time and space raises some significant problems. Because MicroGrids embed new generation within the existing radial distribution system, system upgrades that would otherwise be necessary to meet growing load can be postponed or entirely avoided. Ideally a price signal could be delivered to customers within the distribution system at times of increasing congestion in a form that would encourage MicroGrid development and investment in generation and/or load control to mitigate the congestion. However, this is difficult in practice. The design of distribution systems in densely populated areas is quite flexible so that any one end-use load could be served by several alternative system

configurations. Thus, the congestion costs seen by any one MicroGrid would depend on a somewhat arbitrary configuration of the network that could change abruptly, thus disrupting the economics dependent on that configuration.

MicroGrid participation in markets is both possible and desirable, but there are some likely limits to it. The low voltages of the MicroGrid will inhibit its ability to efficiently deliver energy beyond the substation, and provision of ancillary services will be similarly limited. One service that the MicroGrid can readily provide, however, is interruptible load, taking advantage of its on-site generation and control schemes to protect sensitive loads. This could be a valuable contribution to the overall health of the power system as market responses to load changes become less and less feasible when response times must be within seconds or minutes.

Finally, as mentioned above, if sensitive loads are widely provided for locally within MicroGrids, then the appropriate target level of utility reliability could change significantly. Reliability of the bulk power system could be set at levels appropriate for the task of moving large quantities of power from remote generating sources to load concentrations rather than at a perceived maximum acceptable level of failure that is responsive to sensitive loads served by the system. In other words, if the burden of having to meet the reliability requirements of sensitive end uses moves away from the bulk power system, the bulk power system can adopt a reliability level best suited to its primary purpose.

8. Summary

Small DER may best meet customers' needs and add benefit to the utility grid if these resources are organized into MicroGrids operated as single, controllable systems that can connect to the utility grid or operate independently; this is a new approach for integrating DER into the utility distribution system.

The benefits of a MicroGrid include:

1. To its customers, cost-efficient provision of reliable, high-quality power that meets the requirements of sensitive loads and takes advantage of the opportunities to use waste heat. The small size of individual sources allow placement flexibility to optimize the needs of electrical and/or heat loads.
2. To the utility grid, a MicroGrid operates as a single, controllable system such as a dispatchable load that can reduce grid congestion and offset the need for new generating capacity.